

AD-A103 859

WISCONSIN UNIV-MADISON MATHEMATICS RESEARCH CENTER
A DUAL DIFFERENTIABLE EXACT PENALTY FUNCTION. (U)

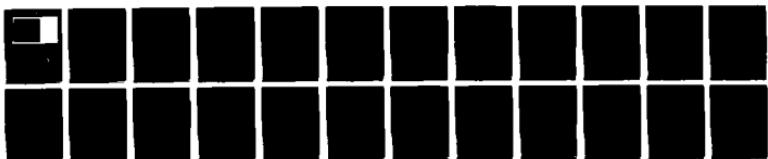
F/6 12/1

AUG 81 S - HAN, O L MANGASARIAN
UNCLASSIFIED MRC-TSR-2257

DAAG29-80-C-0041

NL

1 - 1
2 - 1
3 - 1



END
DATE
FILED
O 81
DTIC

ADA103859

LEVEL

MRC Technical Summary Report #2257

A DUAL DIFFERENTIABLE EXACT PENALTY
FUNCTION

S. -P. Han and O. L. Mangasarian

**Mathematics Research Center
University of Wisconsin-Madison
610 Walnut Street
Madison, Wisconsin 53706**

August 1981

~~Received July 31, 1981~~

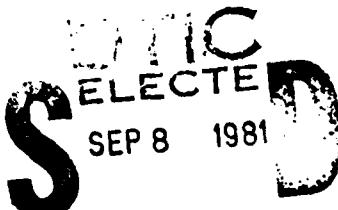
DMC FILE COPY

Sponsored by

U. S. Army Research Office
P. O. Box 12211
Research Triangle Park
North Carolina 27709

Approved for public release
Distribution unlimited

National Science Foundation
Washington, D. C. 20550



A

81 9 08 108

UNIVERSITY OF WISCONSIN - MADISON
MATHEMATICS RESEARCH CENTER

A DUAL DIFFERENTIABLE EXACT PENALTY FUNCTION

S.-P. Han and O. L. Mangasarian

Technical Summary Report, #2257
August 1981

ABSTRACT

A new penalty function is associated with an inequality constrained nonlinear programming problem via its dual. This penalty function is globally differentiable if the functions defining the original problem are twice globally differentiable. In addition, the penalty parameter remains finite. This approach reduces the original problem to a simple problem of maximizing a globally differentiable function on the product space of a Euclidean space and the nonnegative orthant of another Euclidean space. Many efficient algorithms exist for solving this problem. For the case of quadratic programming, the penalty function problem can be solved effectively by successive overrelaxation (SOR) methods which can handle huge problems while preserving sparsity features.

AMS (MOS) Subject Classifications: 90C30, 90C20

Key Words: Nonlinear programming, quadratic programming, penalty functions, SOR methods

Work Unit Number 5 - Operations Research

Sponsored by the United States Army under Contract No. DAAG29-80-C-0041,
This material is based upon work supported by the National Science
Foundation under Grants No. MCS-790166 and ENG-7903881.

SIGNIFICANCE AND EXPLANATION

The problem of minimizing a function of several variables subject to inequality constraints is reduced to the problem of maximizing a smooth function subject to nonnegativity constraints. The latter problem can be easily solved by many known efficient methods. Very large quadratic problems can be solved by using successive over-relaxation methods which will preserve any sparsity the original problem may have.

Accession For	
NTIS GRAF	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	

The responsibility for the wording and views expressed in this descriptive summary lies with MRC, and not with the authors of this report.

A DUAL DIFFERENTIABLE EXACT PENALTY FUNCTION

S. -P. Han and O. L. Mangasarian

1. Introduction

It is well known that exterior penalty functions [6,13] in mathematical programming suffer from one of two difficulties. Either the Hessian of the penalty function becomes ill-conditioned as the penalty parameter approaches infinity [6,20], or the penalty function is nondifferentiable [13]. There have been, however, attempts at obtaining penalty functions which are both differentiable and for which the penalty parameter remains finite [8,3,4,1]. We present here a different and an extremely simple penalty function which, by taking advantage of the structure of the dual problem, results in a penalty function which is differentiable and for which the penalty parameter remains finite. The key idea behind the present approach is extremely simple and is best illustrated by the following equality-constrained minimization problem

$$\underset{x \in R^n}{\text{minimize}} \quad f(x) \quad \text{subject to} \quad h(x) = 0$$

where f and h are differentiable functions from the n -dimensional real Euclidean space R^n into R and R^k respectively. The classical exterior penalty problem for this problem is

$$\underset{x \in R^n}{\text{minimize}} \quad f(x) + \frac{\alpha}{2} \|h(x)\|^2$$

where α is a positive penalty parameter and $\|\cdot\|$ denotes the 2-norm.

At stationary points of the penalty problem we have

$$\nabla f(x) + \alpha \nabla h(x)^T h(x) = 0$$

Sponsored by the United States Army under Contract No. DAAG29-80-C-0041.
This material is based upon work supported by the National Science
Foundation under Grants No. MCS-790166 and ENG-7903881.

where $\nabla f(x)$ is the $n \times 1$ gradient of f , $\nabla h(x)$ is the $k \times n$ Jacobian of h and the superscript T denotes the transpose. In order for this condition to approach the stationarity conditions for the minimization problem, which are

$$\nabla f(x) + \nabla h(x)^T u = 0, \quad h(x) = 0$$

where u is an $k \times 1$ vector of Lagrange multipliers, the quantity $ah(x)$ must approach u . Since $h(x) = 0$, it turns out that in general α must approach ∞ . There are exceptions. For example if $u = 0$ then α need not approach ∞ . This is an exceptional case which does not hold in general for the original minimization problem.

However, if we consider the Wolfe dual [22,15] to an inequality constrained minimization problem, then the optimal Lagrange multiplier associated with the equality constraint of the dual is zero provided that the Hessian of the Lagrangian is nonsingular at the optimum. Hence for the exterior penalty problem associated with Wolfe dual we can show (Theorems 1 to 4) that under rather natural conditions the penalty parameter remains finite. Hence we can obtain a globally differentiable penalty function with a finite penalty parameter. Because our penalty problem formulation depends in an essential manner on the dual problem, our results are local results in the absence of convexity, and become global results if convexity is assumed. Because our penalty function is smooth and its parameter is finite it has important computational implications. For example, fast methods of smooth optimization could be used to directly optimize the differentiable penalty function (Algorithm 1), or the function may be used as in [12] in enlarging the convergence region

of fast but locally convergent algorithms [9,11]. In addition, for positive definite quadratic programming problems, our penalty function can be used to derive a successive overrelaxation (SOR) algorithm without the need to invert the underlying positive definite matrix of the problem (Algorithm 2). SOR algorithms have proved to be successful in solving linear programming problems [17] and have the potential for solving enormous problems that cannot be tackled by pivotal methods while at the same time preserving the sparsity of the problem.

Besides this Introduction, this paper contains two sections. In Section 2 we treat the general nonlinear programming problem while in Section 2 we specialize to the quadratic programming case to obtain sharper results. Section 1 contains theorems relating stationary points, local and global optima of the nonlinear inequality constrained problem to those of the penalty problem. We also give a simple gradient projection algorithm for optimizing the penalty function. In Section 3 we have similar results for the quadratic programming case. We also present an SOR method for quadratic programming which is a generalization of the SOR method used with successful computational results on linear programming [17].

We briefly describe our notation. All vectors in R^n will be column vectors unless transposed to a row vector by the superscript T. R_+^n will denote the nonnegative orthant $\{x | x \in R^n, x \geq 0\}$. For x in R^n , x_i , $i=1, \dots, n$, will denote its i th component, while x_+ will denote a vector in R^n with components $(x_+)_i = \max\{x_i, 0\}$, $i=1, \dots, n$ and $\|x\|$ will denote the Euclidean norm $(x^T x)^{1/2}$. For an $m \times n$ real matrix A , A_i

will denote the i th row, $A \cdot j$ the j th column, and if $I \subset \{1, \dots, m\}$, $J \subset \{1, \dots, n\}$ then A_I will denote the submatrix with rows A_i , $i \in I$, A_J will denote the submatrix with columns $A \cdot j$, $j \in J$, and A_{IJ} will denote the submatrix with elements A_{ij} , $i \in I$ and $j \in J$. For a differentiable function $f: \mathbb{R}^n \rightarrow \mathbb{R}$, $\nabla f(x)$ will denote the $n \times 1$ gradient vector, while for a differentiable function $g: \mathbb{R}^n \rightarrow \mathbb{R}^m$, $\nabla g(x)$ will denote the $m \times n$ Jacobian matrix. For a twice differentiable function $L: \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$, $\nabla_x L(x, u)$ will denote the $n \times 1$ gradient with respect to x , $\nabla_u L(x, u)$ will denote $m \times 1$ gradient with respect to u , $\nabla^2 L(x, u)$ will denote $(n+m) \times (n+m)$ Hessian with respect to both x and u whose submatrix components are denoted as follows

$$\nabla^2 L(x, u) = \begin{bmatrix} \nabla_{xx} L(x, u) & \nabla_{xu} L(x, u) \\ \nabla_{ux} L(x, u) & \nabla_{uu} L(x, u) \end{bmatrix}$$

For a nonlinear programming problem such as (1) below, a point $(\bar{x}, \bar{u}) \in \mathbb{R}^{n+m}$ satisfying the Karush-Kuhn-Tucker conditions (1') is said to be a KKT point, while \bar{x} is said to be a stationary point of (1). Whenever a point (\bar{x}, \bar{u}) is a KKT point, the differentiability of f and g at \bar{x} is implicitly assumed.

2. The General Nonlinear Programming Problem

We consider here the problem

$$\underset{x \in \mathbb{R}^n}{\text{minimize}} \quad f(x) \quad \text{subject to} \quad g(x) \leq 0 \quad (1)$$

where f is a function from the n -dimensional real Euclidean space \mathbb{R}^n into the reals and g is from \mathbb{R}^n into \mathbb{R}^m . Associated with this problem is the Wolfe dual [22,15]

$$\underset{(x,u) \in \mathbb{R}^{n+m}}{\text{maximize}} \quad L(x,u) \quad \text{subject to} \quad \nabla_x L(x,u) = 0, \quad u \geq 0 \quad (2)$$

$$\text{where } L(x,u) := f(x) + u^T g(x)$$

Our penalty function is derived from (2) by constructing an exterior penalty function for the equality constraints only. Thus we define the penalty function

$$\theta(x,u,\gamma) := L(x,u) - \frac{\gamma}{2} \|\nabla_x L(x,u)\|^2 \quad (3)$$

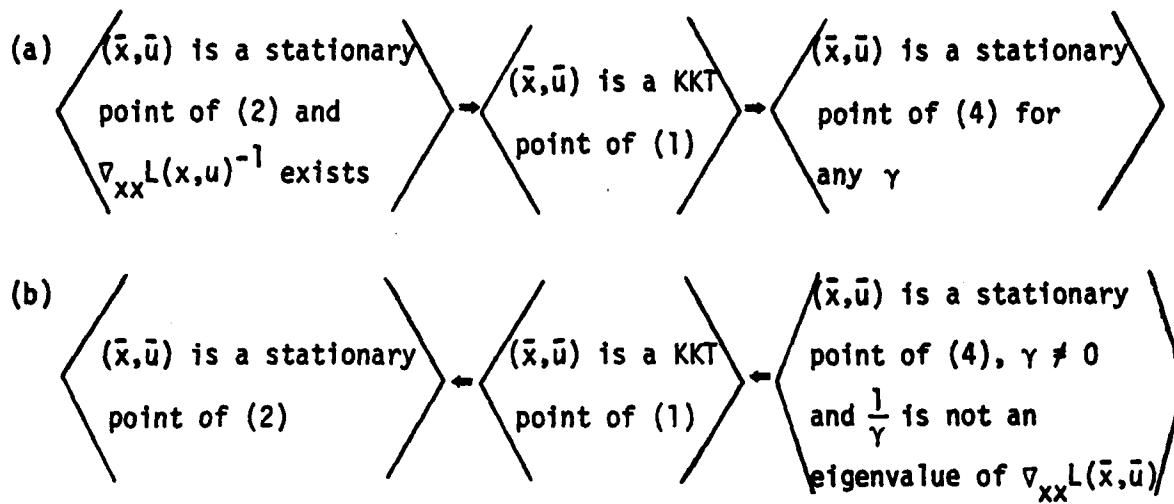
and consider the penalty problem

$$\underset{\substack{(x,u) \in \mathbb{R}^{n+m} \\ u \geq 0}}{\text{maximize}} \quad \theta(x,u,\gamma) \quad (4)$$

which is differentiable on \mathbb{R}^{n+m} when f and g are differentiable on \mathbb{R}^n . We shall relate various stationary and solution points of problems (1), (2) and (4). We begin with a simple but useful result.

Theorem 1 (Equivalence of stationary points of (1), (2) and (4))

Let f and g be twice continuously differentiable at \bar{x} . Then



Proof

The proof follows directly by writing the Karush-Kuhn-Tucker conditions [15] (1'), (2') and (4') for problems (1), (2) and (4) respectively as follows

$$\nabla_x L(\bar{x}, \bar{u}) = 0, g(\bar{x}) \leq 0, \bar{u}^T g(\bar{x}) = 0, \bar{u} \geq 0 \quad (1')$$

For some $\bar{v} \in \mathbb{R}^n$:

$$\begin{aligned}
 \nabla_x L(\bar{x}, \bar{u}) - \nabla_{xx} L(\bar{x}, \bar{u}) \bar{v} &= 0 \\
 g(\bar{x}) - \nabla g(\bar{x}) \bar{v} &\leq 0 \\
 \bar{u}^T (g(\bar{x}) - \nabla g(\bar{x}) \bar{v}) &= 0 \\
 \bar{u} &\geq 0 \\
 \nabla_x L(\bar{x}, \bar{u}) &= 0
 \end{aligned} \tag{2'}$$

$$\begin{aligned}
 (I - \gamma \nabla_{xx} L(\bar{x}, \bar{u})) \nabla_x L(\bar{x}, \bar{u}) &= 0 \\
 g(\bar{x}) - \gamma \nabla g(\bar{x}) \nabla_x L(\bar{x}, \bar{u}) &\leq 0 \\
 \bar{u}^T (g(\bar{x}) - \gamma \nabla g(\bar{x}) \nabla_x L(\bar{x}, \bar{u})) &= 0 \\
 \bar{u} &\geq 0
 \end{aligned} \tag{4'}$$

□

In the next result we establish, under appropriate assumptions, the local concavity of $\theta(x, u, \gamma)$ in both the variables x and u .

Theorem 2 (Negative semidefiniteness and definiteness of $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$)

Let (\bar{x}, \bar{u}) be a KKT point of (1), let f and g be twice continuously differentiable at \bar{x} and let $\nabla_{xx} L(\bar{x}, \bar{u})$ be positive definite with minimum eigenvalue $\bar{\rho} > 0$. Then for $\gamma \geq \frac{1}{\bar{\rho}}$, (\bar{x}, \bar{u}) is a stationary point of (4) and the Hessian $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$ with respect to (x, u) is negative semidefinite. If in addition $\gamma > \frac{1}{\bar{\rho}}$ and $\nabla g(\bar{x})$ has linearly independent rows, then $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$ is negative definite and hence (\bar{x}, \bar{u}) is a strict local maximum of (4).

Proof

By Theorem 1, (\bar{x}, \bar{u}) satisfies the KKT conditions (4') for problem (4). We have from (3) when f and g are differentiable at x that

$$\nabla \theta(x, u, \gamma) = \begin{bmatrix} (I - \gamma \nabla_{xx} L(x, u)) \nabla_x L(x, u) \\ g(x) - \gamma \nabla g(x) \nabla_x L(x, u) \end{bmatrix} \tag{5}$$

Recalling that $\nabla_x L(\bar{x}, \bar{u}) = 0$ we have that

$$\nabla^2 \theta(\bar{x}, \bar{u}, \gamma) = \begin{bmatrix} \nabla_{xx} L(\bar{x}, \bar{u})(I - \gamma \nabla_{xx} L(\bar{x}, \bar{u})) & (I - \gamma \nabla_{xx} L(\bar{x}, \bar{u})) \nabla g(\bar{x})^T \\ \nabla g(\bar{x})(I - \gamma \nabla_{xx} L(\bar{x}, \bar{u})) & -\gamma \nabla g(\bar{x}) \nabla g(\bar{x})^T \end{bmatrix} \quad (6)$$

Define

$$C := \nabla_{xx} L(\bar{x}, \bar{u}) \quad \text{and} \quad A := \nabla g(\bar{x}) \quad (7)$$

then

$$\nabla^2 \theta(\bar{x}, \bar{u}, \gamma) = \begin{bmatrix} C(I - \gamma C) & (I - \gamma C)A^T \\ A(I - \gamma C) & -\gamma AA^T \end{bmatrix} = \begin{bmatrix} C & A^T \\ A & 0 \end{bmatrix} - \gamma \begin{bmatrix} C & A^T \\ A & 0 \end{bmatrix}$$

and for $\gamma \geq \frac{1}{\bar{\rho}}$ we have that

$$\begin{aligned} (x^T u^T) \nabla^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ u \end{pmatrix} &= x^T C x + 2x^T A u - \gamma \|Cx + A^T u\|^2 \\ &= -x^T C x + 2x^T (Cx + A^T u) - \gamma \|Cx + A^T u\|^2 \\ &\leq -\bar{\rho} \|x\|^2 + 2\|x\| \|Cx + A^T u\| - \gamma \|Cx + A^T u\|^2 \\ &= -\bar{\rho} \left(\|x\| - \frac{1}{\bar{\rho}} \|Cx + A^T u\| \right)^2 - (\gamma - \frac{1}{\bar{\rho}}) \|Cx + A^T u\|^2 \\ &\leq 0 \end{aligned}$$

Hence $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$ is positive semidefinite for $\gamma \geq \frac{1}{\bar{\rho}}$. If $\begin{pmatrix} x \\ u \end{pmatrix} \neq 0$ then we consider two cases:

Case I: $Cx + A^T u \neq 0$. For this case it follows from $\gamma > \frac{1}{\bar{\rho}}$ that $(x^T u^T) \nabla^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ u \end{pmatrix} < 0$.

Case II: $Cx + A^T u = 0$ and $\begin{pmatrix} x \\ u \end{pmatrix} \neq 0$. For this case we have that $x \neq 0$, else $u^T A = 0$, $u \neq 0$, which contradicts the assumption that the rows of A are linearly independent. Hence

$$(x^T u^T) \nabla^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ u \end{pmatrix} = -x^T Cx < 0$$

where the last inequality follows from the assumption that C is positive definite.

Thus in either case $(x^T u^T) \nabla^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ u \end{pmatrix} < 0$ for $(x, u) \neq 0$ and $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$ is negative definite for $\gamma > \frac{1}{\rho}$ and (\bar{x}, \bar{u}) is a strict local maximum of (4) [6,13]. \square

The assumption in Theorem 2 that $\nabla g(\bar{x})$ has full row rank is restrictive, but apparently it is the best we can do if we require that $\nabla^2 \theta(\bar{x}, \bar{u}, \gamma)$ be negative definite. A natural relaxation is to merely ask for conditions that ensure that (\bar{x}, \bar{u}) is a strict local maximum of (4). It turns out that such a relaxation can be reflected in replacing the linear independence of the rows of $\nabla g(\bar{x})$ by the less stringent requirement of the linear independence of the gradients of the active constraints only as follows.

Theorem 3 (Strict local maximum of $\theta(x, u, \gamma)$)

The last sentence of Theorem 2 can be replaced by the following: If in addition $\gamma > \frac{1}{\rho}$ and $\nabla g_i(\bar{x})$ are linearly independent for $i \in J$ where

$$J = \{i | g_i(\bar{x}) = 0, i = 1, \dots, m\} \quad (8)$$

then (\bar{x}, \bar{u}) is a strict local maximum of (4).

Proof

Let $A_J = \nabla g_J(\bar{x})$. From the proof of Theorem 2, by replacing A by A_J , we have that $\nabla_{JJ}^2 \theta(\bar{x}, \bar{u}, \gamma)$ is negative definite for $\gamma > \frac{1}{\bar{p}}$ where

$$\nabla_{JJ}^2 \theta(\bar{x}, \bar{u}, \gamma) := \begin{bmatrix} C(I-\gamma C) & (I-\gamma C)A_J^T \\ A_J(I-\gamma C) & -\gamma A_J A_J^T \end{bmatrix} = \begin{bmatrix} C & A_J^T \\ A_J & 0 \end{bmatrix} - \gamma \begin{bmatrix} C \\ A_J \end{bmatrix} \begin{bmatrix} C & A_J^T \\ A_J & 0 \end{bmatrix} \quad (9)$$

We establish now that (\bar{x}, \bar{u}) is a strict local maximum by (4) by establishing the second order sufficient optimality condition [6,13].

Note from (5) that $\nabla_u \theta(\bar{x}, \bar{u}, \gamma) = g(\bar{x})$, and since the optimal multiplier associated with the nonnegativity constraint $u \geq 0$ is $-\nabla_u \theta(\bar{x}, \bar{u}, \gamma)$, hence the second order sufficient optimality condition for (4) is then

$$0 \neq \begin{pmatrix} x \\ u \end{pmatrix} = \begin{pmatrix} x \\ u_E = 0 \\ u_G \geq 0 \\ u_H \end{pmatrix} \Rightarrow (x^T u_E^T u_G^T u_H^T) \nabla_{JJ}^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ x_E \\ u_G \\ u_H \end{pmatrix} < 0 \quad (10)$$

where

$$E = \{i | \bar{u}_i = 0, g_i(\bar{x}) < 0\}$$

$$G = \{i | \bar{u}_i = 0, g_i(\bar{x}) = 0\}$$

$$H = \{i | \bar{u}_i > 0, g_i(\bar{x}) = 0\}$$

Since $J = G \cup H$ it follows that the second order condition (10) can be rewritten as

$$0 \neq \begin{pmatrix} x \\ u_G \geq 0 \\ u_H \end{pmatrix} \Rightarrow (x^T u_J^T) \nabla_{JJ}^2 \theta(\bar{x}, \bar{u}, \gamma) \begin{pmatrix} x \\ u_J \end{pmatrix} < 0 \quad (11)$$

Condition (11) is automatically satisfied for $\gamma > \frac{1}{\bar{\rho}}$ because we have already established that $\nabla_{JJ}^2 \theta(\bar{x}, \bar{u}, \gamma)$ is negative definite for $\gamma > \frac{1}{\bar{\rho}}$. \square

So far no convexity assumptions have been made anywhere and consequently all our results are local results. We can globalize some of our results if we assume that f is uniformly strictly convex and g is convex on \mathbb{R}^n . In fact we can show then that for each local solution $(x(\gamma), u(\gamma))$ of (4), $x(\gamma)$ is the unique global solution of (1). In particular we have the following.

Theorem 4 (Stationary points of (4) as global solutions of (1) and (2))

Let f and g be convex and twice continuously differentiable on \mathbb{R}^n , let

$$y^T \nabla^2 f(x) y \geq v \|y\|^2 \text{ for all } x, y \in \mathbb{R}^n \text{ and some } v > 0, \quad (12)$$

and let $\gamma > \frac{1}{v}$. For every stationary point $(x(\gamma), u(\gamma))$ of (4), $x(\gamma)$ is independent of γ and $x(\gamma) = \bar{x}$, where \bar{x} is the unique solution of (1).

Proof

For x, y in \mathbb{R}^n and $u \in \mathbb{R}^m$, $u \geq 0$ we have that

$$y^T \nabla_{xx} L(x, u) y \geq y^T \nabla^2 f(x) y \geq v \|y\|^2 \quad (13)$$

Hence $\nabla_{xx} L(x, u)$ is positive definite for all $u \geq 0$ and its smallest eigenvalue $\rho(x, u)$ satisfies the inequality $\rho(x, u) \geq v$. By Theorem 1(b) every stationary point $(x(\gamma), u(\gamma))$ satisfies the KKT conditions (1') of

(1). Since f is strictly convex and g is convex, $x(\gamma)$ must equal the unique solution \bar{x} of (1) and $(\bar{x}, u(\gamma))$ must solve (2) [15]. \square

We note that problem (4) can be used directly to construct an algorithm for solving the original problem. For example we can easily prescribe a Levitin-Poljak gradient projection algorithm [14] or a superlinearly convergent quasi-Newton algorithm [10,7,9,11,21]. The key observation to make here is that the projection operation here is an extremely simple one, namely projection on $\mathbb{R}^n \times \mathbb{R}_+^m$. We give below the simplest gradient projection algorithm for solving (4) and its convergence to a KKT point of (1).

Algorithm 1 (Gradient projection algorithm for (4))

Choose $\gamma > 0$ and any $(x^0, u^0) \in \mathbb{R}^n \times \mathbb{R}_+^m$. Having (x^i, u^i) compute (x^{i+1}, u^{i+1}) as follows:

$$\text{Direction choice: } p^i = (I - \gamma \nabla_{xx} L(x^i, u^i)) \nabla_x L(x^i, u^i)$$

$$q^i = (u^i + g(x^i) - \gamma \nabla g(x^i) \nabla_x L(x^i, u^i))_+ - u^i$$

$$\text{Stepsize choice: } (x^{i+1}, u^{i+1}) = (x^i + \lambda^i p^i, u^i + \lambda^i q^i)$$

where λ^i is chosen such that

$$\theta(x^i + \lambda^i p^i, u^i + \lambda^i q^i, \gamma) = \max_{\lambda} \{\theta(x^i + \lambda p^i, u^i + \lambda q^i, \gamma) \mid u^i + \lambda q^i \geq 0\}$$

where θ is defined by (3).

By standard convergence results [14] and by Theorem 1 we have.

Theorem 5 (Convergence of Algorithm 1)

Let f and g be thrice differentiable on \mathbb{R}^n . Each accumulation point (\bar{x}, \bar{u}) of the sequence $\{(x^i, u^i)\}$ generated by the gradient projection Algorithm 1, such that $\frac{1}{\gamma}$ is not an eigenvalue of $\nabla_{xx} L(\bar{x}, \bar{u})$, is a KKT point of (1).

3. The Quadratic Programming Problem

In this section we specialize our results to the quadratic programming problem and obtain some sharper results. However the principal purpose of this section is to describe an SOR method for solving the quadratic programming problem which does not require the inversion of the matrix defining the quadratic term [17]. This should substantially widen the applicability of SOR methods to mathematical programming problems which have hitherto been limited principally to the minimization of quadratic functions on the nonnegative orthant [16,17,18]. The principal advantages of SOR methods are their ability to handle extremely large problems and to preserve sparsity.

We shall consider here the quadratic program

$$\underset{x \in \mathbb{R}^n}{\text{minimize}} \quad \frac{1}{2} x^T C x + d^T x \quad \text{subject to } Ax \leq b \quad (14)$$

where C is an $n \times n$ symmetric matrix, A is an $m \times n$ matrix, d is in \mathbb{R}^n and b is in \mathbb{R}^m . The dual to this problem obtained from (2) is

$$\underset{(x,u) \in \mathbb{R}^{n+m}}{\text{maximize}} \quad \frac{1}{2} x^T C x + d^T x + u^T (Ax - b) \quad \text{subject to } Cx + d + A^T u = 0, u \geq 0 \quad (15)$$

We note in passing that the standard quadratic programming dual [5,15] obtained by substituting from the equality constraint into the objective function of (15)

$$\underset{(x,u) \in \mathbb{R}^{n+m}}{\text{maximize}} \quad -\frac{1}{2} x^T C x - b^T u \quad \text{subject to } Cx + d + A^T u = 0, u \geq 0 \quad (16)$$

cannot be used to obtain a differentiable exact penalty function because the optimal multiplier associated with the equality constraint in (15) is zero when C is nonsingular, whereas it is equal to x in (16) also when C is nonsingular [15].

The penalty function associated with (15) is

$$\phi(x, u, \gamma) := \frac{1}{2} x^T C x + d^T x + u^T (Ax - b) - \frac{\gamma}{2} \|Cx + A^T u + d\|^2 \quad (17)$$

and the associated penalty problem is

$$\begin{array}{ll} \text{maximize} & \phi(x, u, \gamma) \\ (x, u) \in \mathbb{R}^{n+m} \\ u \geq 0 \end{array} \quad (18)$$

We have as an immediate consequence of Theorems 2 and 3 the following.

Theorem 6 (Concavity and strict concavity of $\phi(x, u, \gamma)$)

Let C be positive definite with minimum eigenvalue $\bar{\rho} > 0$. Then for $\gamma \geq \frac{1}{\bar{\rho}}$, $\nabla^2 \phi(x, u, \gamma)$ is negative semidefinite and hence $\phi(x, u, \gamma)$ is a concave function of (x, u) on \mathbb{R}^{n+m} . If in addition $\gamma > \frac{1}{\bar{\rho}}$ and A has linearly independent rows, then $\nabla^2 \phi(x, u, \gamma)$ is negative definite and hence $\phi(x, u, \gamma)$ is a strictly concave function on \mathbb{R}^{n+m} . If $\gamma > \frac{1}{\bar{\rho}}$ and only A_i , $i \in J$ are linearly independent where

$$J = \{i | A_i \bar{x} = b_i, i=1, \dots, m\}$$

and (\bar{x}, \bar{u}) is a KKT point of (1), then (\bar{x}, \bar{u}) is a strict global maximum solution of (18).

Corollary 1 Let $\{x | Ax \leq b\}$ be nonempty, let C be positive definite with least eigenvalue $\bar{\rho} > 0$. Then for each $\gamma \geq \frac{1}{\bar{\rho}}$, problem (18) is a concave quadratic maximization problem which possesses a solution $(x(\gamma), u(\gamma))$ with $x(\gamma)$ independent of γ and $x(\gamma) = \bar{x}$ where \bar{x} is the unique global solution of (14).

With the help of the SOR scheme of [16] we can solve iteratively the quadratic program (18) in $R^n \times R^m_+$ and thereby obtain a solution to (14). It will be convenient for that purpose to have the following expressions at hand

$$\nabla \phi(x, u, \gamma) = \begin{bmatrix} (I - \gamma C)(Cx + A^T u + d) \\ Ax - b - \gamma A(Cx + A^T u + d) \end{bmatrix} \quad (19)$$

$$\nabla^2 \phi(x, u, \gamma) = \begin{bmatrix} C(I - \gamma C) & (I - \gamma C)A^T \\ A(I - \gamma C) & -\gamma AA^T \end{bmatrix} \quad (20)$$

An SOR method for solving the quadratic program (18) with relaxation factor $\omega \in (0, 2)$ can be given as follows then

$$x_j^{i+1} = x_j^i + \frac{\omega}{(\nabla_{xx} \phi(x^i, u^i, \gamma))_{jj}} \nabla_{x_j} \phi(x_1^{i+1}, \dots, x_{j-1}^{i+1}, x_j^i, \dots, x_n^{i+1}, u^i, \gamma) \quad j=1, \dots, n \quad (21)$$

$$u_j^{i+1} = (u_j^i + \frac{\omega}{(\nabla_{uu} \phi(x^i, u^i, \gamma))_{jj}} \nabla_{u_j} \phi(x_1^{i+1}, u_1^{i+1}, \dots, u_{j-1}^{i+1}, u_j^i, \dots, u_m^{i+1}, \gamma))_+ \quad j=1, \dots, m$$

We spell out our SOR scheme in detail now.

Algorithm 2 (SOR scheme for (18))

Choose $\omega \in (0, 2)$, $\gamma > \max_j \left\{ \frac{c_{jj}}{\|c_j\|^2} \mid c_j \neq 0 \right\}$, $\frac{1}{\gamma} \neq \text{an eigenvalue of } C$

and $(x^0, u^0) \in R^n \times R^m_+$. Having (x^i, u^i) compute (x^{i+1}, u^{i+1}) as follows:

$$x_j^{i+1} = x_j^i + \frac{\omega}{C_{jj} - \gamma \|C_j\|^2} ((I_j - \gamma C_j) \left(\sum_{\ell=1}^{j-1} C_{\cdot \ell} x_{\ell}^{i+1} + \sum_{\ell=j}^n C_{\cdot \ell} x_{\ell}^i + A^T u^i + d \right))$$

\leftarrow Set to 1 if $C_j = 0$ \leftarrow For $j > 1$ only

$j = 1, \dots, n$

$$u_j^{i+1} = (u_j^i + \frac{\omega}{-\gamma \|A_j\|^2} (A_j x^{i+1} - b_j - \gamma A_j (C x^{i+1} + \sum_{\ell=1}^{j-1} (A^T)_{\cdot \ell} u_{\ell}^{i+1} + \sum_{\ell=j}^m (A^T)_{\cdot \ell} u_{\ell}^i + d)))$$

\leftarrow For $j > 1$ only

$j = 1, \dots, m$

Remark 1

The only implicit assumption in Algorithm 2 is that $A_j \neq 0$, $j = 1, \dots, m$. This assumption imposes no restrictions whatsoever, since all constraints $A_j x \leq b_j$ of (14) for which $A_j = 0$ are either inconsistent ($b_j < 0$) or else can be discarded.

Remark 2

Note that in Algorithm 2 only linear arrays are needed in distinction from rectangular arrays. That is, we need to access the rows and columns of C and A one at a time. Thus, if the problem is of enormous size and very sparse, then only the nonzero elements need be stored, and this sparsity unlike pivotal algorithms is never lost.

We can now use the convergence theorems of [16] and the theorems of this paper to obtain the following convergence result for the SOR Algorithm 2.

Theorem 7 (Monotonicity and convergence of the SOR Algorithm 2)

For the sequence $\{(x^i, u^i)\}$, $i = 1, 2, \dots$, generated by Algorithm 2

$$\phi(x^{i+1}, u^{i+1}, \gamma) \geq \phi(x^i, u^i, \gamma), \quad i = 0, 1, \dots \quad (22)$$

and each accumulation point (\bar{x}, \bar{u}) of the sequence $\{(x^i, u^i)\}$ is a KKT point of the original quadratic program (14). If in addition C is positive semidefinite then \bar{x} is a global solution of (14).

Proof

Inequality (22) follows from (9) of [16] and by Theorem 2.1 of [16] (\bar{x}, \bar{u}) is a stationary point of (17). By Theorem 1, (\bar{x}, \bar{u}) is a KKT point of (14). When C is positive semidefinite \bar{x} is a global minimum solution of (14) by the sufficiency of the KKT conditions [15]. \square

We note that Theorem 7 does not ensure the existence of an accumulation (\bar{x}, \bar{u}) of the sequence $\{(x^i, u^i)\}$ of Algorithm 2. To ensure that at least one accumulation point exists we need to impose some sort of qualification similar to that of Theorem 2.2 of [16] which will ensure the boundedness of the iterates $\{(x^i, u^i)\}$ of Algorithm 2. In particular we have the following.

Theorem 8 (Boundedness of the iterates of the SOR Algorithm 2)

Let C be positive definite with minimum eigenvalue $\bar{\rho} > 0$, let A have linearly independent columns, let \hat{x} satisfy the constraint qualification $A\hat{x} < b$ and let $\gamma > \frac{1}{\bar{\rho}}$. Then the sequence $\{(x^i, u^i)\}$, $i=1, 2, \dots$, generated by the SOR Algorithm 2 is bounded and $\lim_{i \rightarrow \infty} x^i = \bar{x}$, where \bar{x} is the unique global solution of (14).

Proof

By Theorem 6 the constant Hessian $\nabla^2 \phi(x, u, \gamma)$ defined by (20) is negative semidefinite. We shall assume that the sequence $\{(x^i, u^i)\}$

generated by Algorithm 2 is unbounded and exhibit a contradiction. Without loss of generality suppose that $\|(x^i, u^i)\| \neq 0$ and $\{\|x^i, u^i\|\} \rightarrow \infty$.

Define $z := \begin{pmatrix} x \\ u \end{pmatrix}$, $M := \nabla^2 \phi(x, u, \gamma)$ and $q := \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} := \begin{pmatrix} (I - \gamma C)d \\ -b - \gamma Ad \end{pmatrix}$. Then

$$\phi(x, u, \gamma) = \phi(z, \gamma) = \frac{1}{2} z^T M z + q^T z$$

It follows from (22) and Algorithm 2 for $i=1, 2, \dots$, that $u^i \geq 0$ and

$$\frac{\phi(z^0, \gamma)}{\|z^0\|^2} \leq \frac{\phi(z^i, \gamma)}{\|z^i\|^2} = \frac{1}{2} \frac{z^i^T M z^i}{\|z^i\|^2} + \frac{1}{\|z^i\|} q^T \frac{z^i}{\|z^i\|}.$$

By the Bolzano-Weierstrass Theorem we get that $\left\{ \frac{z^i}{\|z^i\|} \right\}$ has an

accumulation point \bar{y} on the unit sphere in \mathbb{R}^{n+m} satisfying $0 \leq \frac{1}{2} \bar{y}^T M \bar{y}$ and $\bar{y} = \begin{pmatrix} \bar{x} \\ \bar{u} \end{pmatrix}$ with $\bar{x} \in \mathbb{R}^n$ and $\bar{u} \in \mathbb{R}_+^m$. Since M is negative semidefinite it follows that $\bar{y}^T M \bar{y} = 0$ and hence $M \bar{y} = 0$. Since we also have that

$$\frac{\phi(z^0, \gamma)}{\|z^0\|} \leq \frac{\phi(z^i, \gamma)}{\|z^i\|} = \frac{1}{2} \frac{z^i^T M z^i}{\|z^i\|} + \frac{q^T z^i}{\|z^i\|} \leq \frac{q^T z^i}{\|z^i\|}$$

it follows that $0 \leq q^T \bar{y}$. We thus have

$$M \bar{y} = 0, q^T \bar{y} \geq 0, 0 \neq \bar{y} = \begin{pmatrix} \bar{x} \\ \bar{u} \end{pmatrix}, \bar{u} \geq 0 \quad (23)$$

or equivalently

$$\begin{pmatrix} C(I-\gamma C) & (I-\gamma C)A^T \\ A(I-\gamma C) & -\gamma AA^T \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{u} \end{pmatrix} = 0, \quad q_1^T \bar{x} + q_2^T \bar{u} \geq 0, \quad \bar{u} \geq 0, \quad (\bar{x}, \bar{u}) \neq 0 \quad (24)$$

From the generalized Gordan theorem of the alternative [19] (24) is equivalent to either

the rows of $[C(I-\gamma C) \quad (I-\gamma C)A^T]$ are linearly dependent (25)

or

$$\begin{aligned} C(I-\gamma C)v + (I-\gamma C)A^Tw &= (I-\gamma C)d \\ A(I-\gamma C)v - \gamma AA^Tw &> -b - \gamma Ad \end{aligned} \quad (26)$$

has no solution (v, w) in \mathbb{R}^{n+m}

Because $\gamma > \frac{1}{\rho}$ it follows that $I - \gamma C$ is negative definite and that $C(I-\gamma C)$ is nonsingular which contradicts (25). We will show now that (26) also leads to a contradiction. By hypothesis we have that $A\hat{x} < b$. Since the columns of A are linearly independent, there exists a w satisfying

$$A^Tw = d + C\hat{x}$$

and hence

$$A\hat{x} = AC^{-1}(A^Tw - d) < b$$

that is

$$AC^{-1}d - AC^{-1}A^Tw + b > 0$$

or

$$AC^{-1}((I-\gamma C)d - (I-\gamma C)A^Tw) - \gamma AA^Tw > -b - \gamma Ad$$

By defining

$$v = (I - \gamma C)^{-1} C^{-1} ((I - \gamma C)d - (I - \gamma C)A^T w)$$

we get

$$C(I - \gamma C)v + (I - \gamma C)A^T w = (I - \gamma C)d$$

$$A(I - \gamma C)v - \gamma A A^T w > -b - \gamma A d$$

These last two relations contradict (26). Consequently the sequence $\{(x^i, u^i)\}$ is bounded and must have at least one accumulation point. For each accumulation point (\bar{x}, \bar{u}) , \bar{x} must equal the unique solution \bar{x} of (14). Since $\{x^i\}$ is also bounded it must converge to \bar{x} [2]. \square

At this time we do not have any computational experience for the SOR Algorithm 2 for solving the general quadratic programming problem (14). However, for the case when matrix $C = \epsilon I$ where ϵ is a positive number and $\gamma = \frac{1}{\epsilon}$, the penalty problem (18) becomes

$$\begin{array}{ll} \text{Maximize} & -\frac{1}{2} \|A^T u + d\|^2 - \epsilon b^T u \\ u \in \mathbb{R}^m \\ u \geq 0 \end{array} \quad (27)$$

This is precisely the dual of the quadratic program perturbation of [17] associated with the linear program

$$\begin{array}{ll} \text{Minimize} & d^T x \quad \text{subject to} \quad Ax \leq b \\ x \in \mathbb{R}^n \end{array} \quad (28)$$

and which was solved quite successfully by the SOR method proposed here. Thus for at least this special class of quadratic programs computational experience is very encouraging. It is hoped that this experience will carry over to the more general case.

References

1. D. P. Bertsekas: "Enlarging the region of convergence of Newton's method for constrained optimization", Report LIDS-R-985, Laboratory for Information and Decision Systems, MIT, Cambridge, Massachusetts, March 1980.
2. R. C. Buck: "Advanced Calculus", McGraw-Hill, New York, 1965, p. 47.
3. G. DiPillo and L. Grippo: "A new class of augmented Lagrangians in nonlinear programming", SIAM Journal on Control and Optimization 17, 1979, 618-628.
4. G. DiPillo and L. Grippo: "An augmented Lagrangian for inequality constraints in nonlinear programming problems", Report 79-22, Instituto di Automatica, Universita di Roma, June 1979.
5. W. S. Dorn: "Duality in quadratic programming", Quarterly of Applied Mathematics 18, 1960, 155-162.
6. A. V. Fiacco and G. P. McCormick: "Nonlinear programming: sequential unconstrained minimization techniques", Wiley, New York, 1968.
7. J. Fischer: "Proof of convergence for a modification of Goldfarb's algorithm", Mathematics of Operations Research 6, 1981, 233-245.
8. R. Fletcher: "A class of methods for nonlinear programming. III: Rates of convergence", in F. A. Lootsma (editor): "Numerical methods for nonlinear optimization", Academic Press, New York, 1972, 371-381.
9. U. Garcia Palomares and O. L. Mangasarian: "Superlinearly convergent quasi-Newton algorithms for nonlinearly constrained optimization problems", Mathematical Programming 11, 1976, 1-13.
10. D. Goldfarb: "Extension of Davidon's variable metric method to maximization under linear inequality constraints", SIAM Journal on Applied Mathematics 17, 1969, 739-764.
11. S.-P. Han: "Superlinearly convergent variable metric algorithms for general nonlinear programming problems", Mathematical Programming 11, 1976, 263-282.
12. S.-P. Han: "A globally convergent method for nonlinear programming", Journal of Optimization Theory and Applications 22, 1977, 297-309.
13. S.-P. Han and O. L. Mangasarian: "Exact penalty functions in nonlinear programming", Mathematical Programming 17, 1979, 251-269.

14. E. S. Levitin and B. T. Poljak: "Constrained minimization methods", USSR Computational Mathematics and Mathematical Physics (English translation) 6, 1966, 1-50.
15. O. L. Mangasarian: "Nonlinear programming", McGraw-Hill, New York, 1969.
16. O. L. Mangasarian: "Solution of symmetric linear complementarity problems by iterative methods", Journal of Optimization Theory and Applications 22, 1977, 465-485.
17. O. L. Mangasarian: "Iterative solution of linear programs", SIAM Journal on Numerical Analysis 18(4), August 1981.
18. O. L. Mangasarian: "Least-norm linear programming solution as an unconstrained minimization problem", Report 2147, Mathematics Research Center, University of Wisconsin, Madison, December 1980, to appear in Journal of Mathematical Analysis and Applications.
19. O. L. Mangasarian: "A stable theorem of the alternative: an extension of the Gordan theorem", Report 2185, Mathematics Research Center, University of Wisconsin, Madison, March 1981, to appear in Linear Algebra and Its Applications.
20. W. Murray: "Analytical expressions for the eigenvalues and eigenvectors of the Hessian matrices of barrier and penalty functions", Journal of Optimization Theory and Applications 7, 1971, 189-196.
21. M. J. D. Powell: "The convergence of variable metric methods for nonlinearly constrained optimization calculations" in O. L. Mangasarian, R. R. Meyer and S. M. Robinson (editors): "Nonlinear programming 3", Academic Press, New York 1978, 27-63.
22. P. Wolfe: "A duality theorem for nonlinear programming", Quarterly of Applied Mathematics 19, 1961, 239-244.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 2257	2. GOVT ACCESSION NO. <i>AD-A103 859</i>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and subtitle) A DUAL DIFFERENTIABLE EXACT PENALTY FUNCTION	5. TYPE OF REPORT & PERIOD COVERED Summary Report - no specific reporting period	
7. AUTHOR(s) S. -P. Han and O. L. Mangasarian	6. PERFORMING ORG. REPORT NUMBER 8. CONTRACT OR GRANT NUMBER(s) ENG-7903881 DAAG29-80-C-0041 MCS-790166	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mathematics Research Center, University of 610 Walnut Street Wisconsin Madison, Wisconsin 53706	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 5-Operations Research	
11. CONTROLLING OFFICE NAME AND ADDRESS See Item 18 below	12. REPORT DATE August 1981	
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	13. NUMBER OF PAGES 22	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
18. SUPPLEMENTARY NOTES U. S. Army Research Office P. O. Box 12211 Research Triangle Park North Carolina 27709	National Science Foundation Washington, D. C. 20550	
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Nonlinear programming, quadratic programming, penalty functions, SOR methods		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A new penalty function is associated with an inequality constrained nonlinear programming problem via its dual. This penalty function is globally differentiable if the functions defining the original problem are twice globally differentiable. In addition, the penalty parameter remains finite. This approach reduces the original problem to a simple problem of maximizing a globally differentiable function on the product space of a Euclidean space and the nonnegative orthant of another Euclidean space. Many efficient algorithms exist for solving this problem. For the case of quadratic programming, the penalty function problem can be solved effectively by successive overrelaxation (SOR) methods which can handle huge problems while		

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE preserving sparsity features.
1 JAN 73 UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)